NHRP

Natural Hazards Research Platform

Contest 2012-GNS-05

Title: Did artesian groundwater contribute to Christchurch liquefaction and lateral spreading damage?

Leader: Dr Simon Cox
Organisation: GNS Science

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Title: Did artesian groundwater contribute to Christchurch liquefaction and lateral spreading damage?

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Key message for media

Present geotechnical best-practice assessment of liquefaction hazard is focussed on the triggering of the process by which an earthquake causes poorly consolidated, groundwater-saturated, geological materials to temporarily lose strength and stiffness and permanently volumetrically consolidate. Assessments typically only consider the shallow water table position. While liquefied ground presents an engineering challenge, the repeated invasion of properties by ejecta and the resulting differential ground surface subsidence adds a heavy societal cost to this hazard. Our results indicate that where confined groundwater pressure is artesian (above ground) there is an additional driving mechanism for the ejection of liquefied material to the surface, so hazard assessments also need to consider the wider hydrogeologic environment. Built over aquifers with substantial artesian groundwater pressure, the severity of the observed liquefaction damage in Christchurch may be an extreme example that may not be widely applicable elsewhere.

Abstract

'Liquefaction' is commonly used as a verb describing the process when an earthquake causes poorly consolidated, groundwater-saturated, geological materials to lose strength and stiffness, due to increased pore pressure in the material. By way of contrast, the term 'liquefaction' became a New Zealand household noun describing the vast quantities of soul-destroying sand, silt and smelly water that repeatedly inundated properties during the 2010-2011 Canterbury earthquake sequence. Liquefaction verb and noun were extreme in their combined devastation of Christchurch city and provide an extreme example of this natural hazard. This Natural Hazards Platform project utilised an extensive network of groundwater monitoring wells, together with a detailed geotechnical dataset and maps of land-damage collected for Christchurch recovery land-zonation. It aimed to test hypotheses on the redistribution of pressure and/or transport of groundwater into the surficial soils during earthquakes and assess the extent to which artesian groundwater pressure contributed to liquefaction, flooding and lateral spreading damage. We demonstrate strong spatial correlations between the occurrence (and severity) of ejected material and liquefaction-related ground damage with deep groundwater pressure in aquifers beneath the city. Present geotechnical best-practice assessment of liquefaction hazard typically only considers the shallow water table position and assumes a hydrostatic pressure profile below the shallow groundwater surface. While liquefied ground presents an engineering challenge, the repeated invasion of properties by ejecta and the resulting differential ground surface subsidence also adds a heavy societal cost to this hazard. Our results suggest where groundwater pressure is artesian (above ground) there is an additional driving mechanism for the ejection of liquefied material at the surface. Liquefaction triggering is also potentially exacerbated by the transfer of groundwater from deep to shallow aquifers.

Keywords: Christchurch, Canterbury earthquakes, liquefaction, groundwater

Introduction / Background:

Earthquake-induced liquefaction causes ground surface subsidence, lateral spreading, loss of bearing capacity, buoyant rise of buried structures and flow failures [NRC 1985] which occurred at near-unprecedented levels during the Canterbury earthquake sequence of 2010-2011 [e.g. Cubrinovski et al. 2011; Orense et al. 2011; Quigley et al. 2013; Tonkin & Taylor Ltd 2013; van Ballegooy et al. 2014c]. Although potential for liquefaction had been previously anticipated in Christchurch city [Brown & Weeber 1992; CAE 1997; Beca 2004, 2005], due to the co-occurrence of loose to medium density non-plastic soil and a shallow near-surface water table, the severity of liquefaction and degree of consequence in the eastern half of the city was unexpected. Large quantities of sand, silt and smelly water were ejected to the surface and repeatedly inundated people's homes and resulting differential ground surface subsidence which caused extensive damage to the residential building portfolio and significantly deflated societal well-being. Lateral spreading and liquefaction-related land damage affected 50% of the horizontal infrastructure (roads, electricity, waste water and fresh water) and around 50,000 of the 140,000 residential properties [van Ballegooy et al. 2014a; Rogers et al. in press]. Approximately 15,000 residential houses were damaged beyond economic repair, mainly as a result of the differential ground surface subsidence caused by the liquefaction, resulting in widespread displacement of people and disruption of communities. As the Canterbury earthquake sequence evolved into one of the world's largest insurance events, with a significant proportion of monetary cost as a result of poor ground performance, there was also a heavy societal cost associated with the repeated invasion of properties by liquefaction ejecta and the resulting differential ground surface subsidence.

Christchurch is built on an artesian aquifer system. Water in confined aquifers beneath the eastern suburbs is under high-pressure, such that if allowed to flow freely from boreholes 100 m deep, the water will reach more than 5 m above sea level [Wilson 1976; Talbot et al. 1986]. In the coastal region, Canterbury groundwater becomes confined in gravel aquifers by interlayered fine-grained marine/estuarine sediments that form aquitards where they reach thickness of 3 m or more [Brown & Weeber 1992; Weeber 2008]. While the artesian aquifer system provides a quality water supply for the city, it was postulated their presence may have contributed to the degree of liquefaction-induced ground damage during recent earthquakes [Cox et al. 2012]. This study sought to utilise an extensive network of groundwater monitoring wells, together with a detailed geotechnical dataset and maps of land-damage collected for insurance assessment purposes and to inform liquefaction evaluations to determine appropriate foundation repair and rebuilding approaches. We aimed to test hypotheses [Wang 2007; Wang & Manga 2010] on the redistribution of pressure and/or transport of groundwater into the surficial soils during earthquakes and assess the extent to which artesian groundwater pressure contributed to liquefaction, flooding and lateral spreading damage.

Objectives or Research Aims

Objective No. 1
Objective Title: Updated knowledge of pre-earthquake hydrology
Budget: $230k
Objective Achieved? Yes

Discussion

This objective was aimed at developing a groundwater dataset across the Christchurch and near-environs that could be used to characterise both the shallow unconfined water table and piezometric pressures in deeper confined aquifers. We aimed to update aquifer pressure contour maps [e.g. Talbot et al. 1976; Weeber 2008] and compute statistical parameters to define level fluctuation variability, aquifer properties, and degrees of correlation between boreholes using monitoring prior to the earthquakes.

Monitoring by Environment Canterbury (ECan), Christchurch City Council (CCC), and the Earthquake Commission (EQC) provides a very comprehensive public groundwater dataset within the Christchurch urban area and nearby environs (±30 km). ECan is focused on recording groundwater in deeper aquifers, for drinking water supply and irrigation purposes, and maintain a network of ~40 wells with transducers recording at 15 minute intervals, and ~50 wells where weekly-monthly measurements have been collected manually in the study area. The ECan groundwater database also contains ~550 sites where there are irregular observations prior to the earthquake sequence (extended as far back as 1894), such as arising from piezometric surveys or aquifer testing, or other manual measurements. These observations have been used to help constrain interpolation between regular monitoring sites. CCC monitoring is aimed towards the shallower unconfined water table, of importance for flood control and engineering, and they record ~27 sites at weekly-monthly intervals and have long-term records that extend >20 years before the earthquake sequence. Shallow groundwater monitoring was lifted to new levels by EQC following the earthquakes, such that there was a network of >960 shallow piezometers (depths <10 m) that have been dipped monthly, some also with transducers.

One of the earliest issues for geotechnical engineering and land planning following the earthquakes was a need for clear knowledge of the depth of shallow groundwater forming the water table. This project accepted the challenge to provide such information, as it was something also we also needed. We found, however, that the quality of data and reporting we felt compelled to provide required substantial due diligence and care – as it was being used for liquefaction evaluations to determine appropriate foundation repair and rebuilding approaches – and became an involved and complicated process which absorbed considerable time.

Whilst there was a marked improvement in the spatial distribution of post-Darfield Earthquake monitoring data, removing some of the uncertainty in lateral variations in the shallow sub-surface, the observations had to be placed in a temporal context. It needed to be established whether this short snap-shot of groundwater readings (in some places not yet recording a full year's worth of data) reflected the expected behaviour of the shallow groundwater in the long-term, and/or to what extent the earthquakes might have affected the status-quo. Our groundwater assessment attempted to account for any changes in water level and well head elevations relative to sea level, and consider changes in the characteristics of flow between wells and surrounding ground/aquifers. The groundwater surfaces modelled from well measurements also incorporated water levels from local rivers, provided 15th and 85th percentile with median water table positions, and an evaluation as to the scale of both seasonal and inter-annual variations (only one-half of the variation seen in long-term 1990-2010 pre-earthquake monitoring was demonstrably seasonal). The end result was two very substantial reports and datasets [van Ballegooy et al. 2013, 2014b].

Event-specific groundwater surfaces were also developed for confined and semi-confined aquifers, to represent pre-earthquake 'static' piezometric pressures. Wells were classified on the basis of geology, distinguishing those records representing 'deep' aquifers (essentially the Riccarton, Linwood, Burwood and Wainoni gravels and Burnham Formation) from sites recording the shallow unconfined water table in the overlying sediments (Christchurch and upper Springston Formations). Statistical assessment was completed between all wells and used to generate synthetic estimates of event specific levels at the ~550 sites where records did not extend across the earthquake sequence. Surfaces were interpolated by natural neighbours methods [Sibson 1981], using the mean values for the month preceding the earthquakes of 2010 and 2011. Wherever possible data were analysed relative to local ground level, rather than converting to an absolute elevation, to avoid compounding the uncertainties associated with surveying well measuring points and/or ground elevation. An example of the water level relative to ground immediately prior to the Darfield M7.1 earthquake on 4 Sept 2010 is provided in Figure 1.

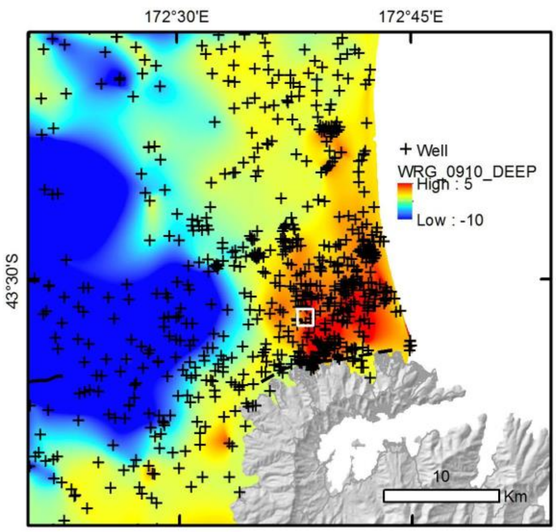

Fig.1 Map showing potentiometric pressure of deep aquifers in September 2010, immediately prior to the M7.1 Darfield earthquake. Groundwater levels are measured as water level relative to ground (WRG), crosses represent well data points. The position of the Christchurch CBD is shown with a white square.

Objective No. 2
Objective Title: Earthquake-induced hydrologic effects defined
Budget: $70k
Objective Achieved? Yes

Discussion:

This objective was aimed at characterising the pressure changes that occurred in aquifers and shallow groundwater as a result of the main earthquakes (Mw7.1 4 Sept 2010, Mw6.3 22 Feb 2011, Mw5.8 and Mw6.0 13 June 2011). Initial work to characterise responses had been completed by Cox et al. [2012]. For this study, we used the complete ECan 15 minute dataset (161 wells) and MatLab code (two separate versions) to quantify responses. In Gulley et al. [2013], we presented a simple model to differentiate between immediate earthquake induced response (spike) and post-seismic change (offset). Spike and offset values generally correlate in terms of sign between the Mw7.1 Sept 2010 and Mw6.2 Feb 2011 earthquakes. For most wells the Mw6.2 Feb 2011 earthquake resulted in larger spikes for wells in the coastal confined aquifers, and there were only small effects in the inland semi-confined aquifers. The most significant feature of this analysis was it highlighted a consistent pattern of response (deeper wells correlate with negative offset and shallower wells correlate with positive offset), thereby providing evidence for the upwards vertical movement of water – adding a further detail to the complex physical processes that lead to liquefaction.

Numerical models of earthquake/groundwater interaction have been developed and tested against observed data. In a paper titled 'On the mechanism of earthquake induced groundwater flow', submitted to Journal of Hydrology and presently being revised, Nick Dudley Ward [in review] a simple mathematical model that further explains and supports the hypothesis in which changes in storativity and aquitard permeability are modelled as shocks permitting coseismic movement of water. Furthermore, a 'hydraulic shock' accounts for essentially instantaneous movement of water on the time-scale of the seismic shaking. The mathematical model is fitted to observed monitoring data.

The near-instantaneous pressure changes in 61 deep wells during each earthquake, derived from the Gulley et al. [2013] code updated by Annabeth Cohen, were interpolated across the Christchurch area. These surfaces provide models of the 'dynamic' earthquake induced pressure changes cause by the earthquakes, which were added to the 'static' pre-earthquake water levels, to yield a 'total' coseismic groundwater pressure relative to ground. The deep aquifer responses to the Darfield Mw7.1 Sept 2010 and Christchurch M6.3 Feb 2011 earthquakes are compared in Figure 2, with above ground (artesian) total pressure shown in red. These data formed the basis for spatial correlations with the occurrence of liquefaction (Objective 4) and a series of manuscripts in prep (see below).

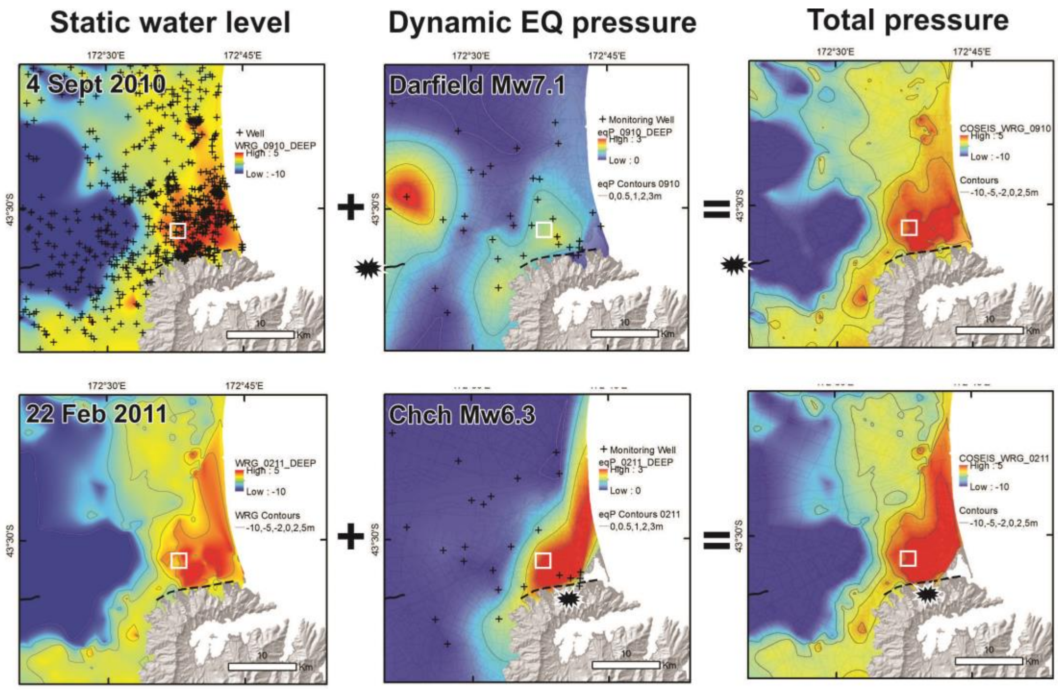

Fig.2 Earthquake-induced hydrologic effects. Left: maps showing potentiometric pressure of 'deep' confined and semi-confined aquifers in September 2010 (upper) and February 2011 (lower), immediately prior to the Mw7.1 Darfield and Mw6.3 Christchurch earthquakes, respectively. Centre: the dynamic pressure changes induced by these earthquakes. Right: the total 'coseismic' pressure. Total and static water levels are measured in metres relative to ground level, dynamic pressure change in metres relative to pre-earthquake value. Crosses represent well data points, stars the earthquake epicentres, white square the Christchurch CBD, and black lines the Greendale and Port Hills faults.

Objective No. 3

Objective Title: Effect of confining layer defined

Budget: $70k

Objective Achieved? Yes

Discussion:

Sustainable development on liquefaction susceptible soil deposits that overlie artesian aquifers are dependent on the thickness of the non-liquefying surface layers (often influenced by the depth to the shallow groundwater surface), the soil characteristics of the underlying liquefying soil layers and as this study has found may also be dependent on the thickness, strength and integrity of the confining layers between the liquefying soil deposits and the underlying artesian aquifer and the amount of pressure in the underlying aquifer. At each borehole location, this objective derived a measure of the vertical hydraulic gradient, being the difference between the levels of the deep (confined) groundwater and shallow (unconfined) water table, divided over the depth of the borehole. Using a combination of the 3D urban geology model [Begg et al. in review] and our own borehole classification we derived an isopach thickness model of the confining aquifer [Figure 3]. Maps of +ve (upwards) and –ve (downwards) flow were generated, scaled according to the strength of the vertical hydraulic pressure gradient, for periods immediately before the M7.1 (Sept 2010), M6.3 (Feb 2011) [Figure 4] and M6.0 (June 2011) earthquakes [cf. Weeber 2008; Lough & Williams 2009].

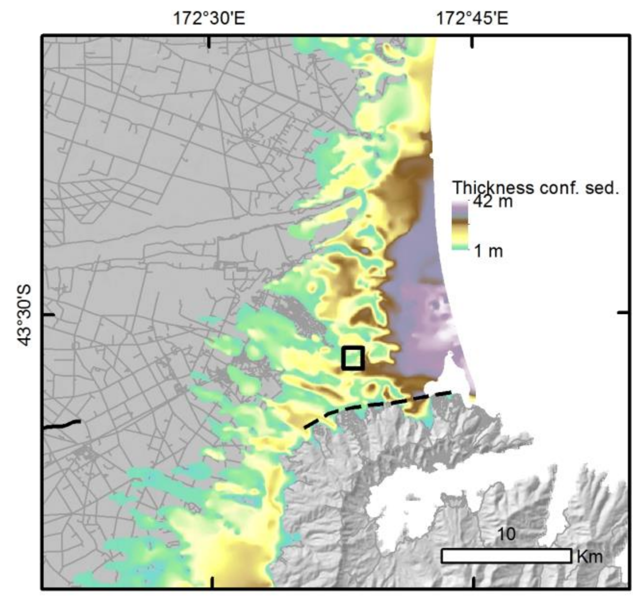

Fig.3 Isopach model of confining sediment thickness across the Christchurch area. Modelled thicknesses range from 1 to 42 m. The Christchurch CBD is shown with a black square.

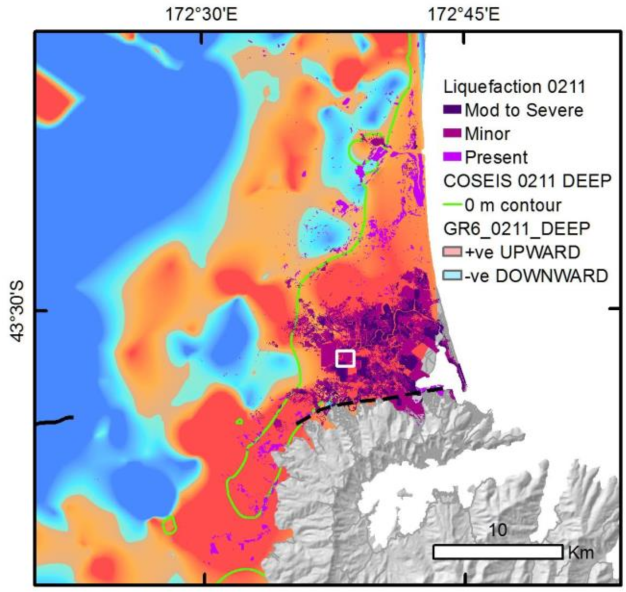

Fig.4 Model of vertical groundwater pressure gradients during the Mw6.3 22 February 2011 earthquake, overlain by a map of liquefaction (pink—to purple coloured according to severity). Red areas have positive, upwards flowing gradients, blue areas negative downwards flowing gradient. The green 0m contour marks the position where groundwater levels were at ground level. East of the line has above ground (artesian) groundwater.

Objective No. 4

Objective Title: Modelling the links and processes

Budget: $90k

Objective Achieved? Yes – some publication work in progress

Discussion

Confusion between the process of liquefaction (verb) and the occurrence of liquefaction (noun) material at the surface that has crept into engineering, science and public perception of liquefaction hazard. Geotechnical testing revolves around whether or not soil will liquefy (verb) during shaking, but as yet only has a limited geotechnical toolbox of empirical indicies to predict whether liquefaction (noun) is likely to be manifested at the ground surface and result in land and building damage.

We undertook spatial modelling and found strong correlations between deep artesian aquifer pressure and the mapped occurrence (and severity) of liquefaction (noun) at a property-scale (50x50m) in Christchurch [using combined dataset from Brackley et al. 2012; Tonkin & Taylor Ltd 2013]. The modelling workflow involved: (1) Dividing the parameter of interest into a series of suitable bins (eg Depth to Groundwater 0-1, 1-2 m etc.); (2) Counting the number of 50 x 50m cells that have either 'None Observed' vs 'Liquefaction Occurs' (with Occurs being either 'Present', 'Minor' or 'Moderate to Severe' liquefaction); then (3) Deriving histograms, cumulative curves, Pr distributions etc.

Spatial analysis shows a clear increase in the probability of observed liquefaction (noun) as the deep groundwater pressure increases. During the 22 Feb 2011 Mw6.3 earthquake, for example, there was a distinct increase in occurrence probability where pressures exceeded ground level (>0m pressure), reaching 30% probability at 5m pressure, and 50% at 7m [Figure 5]. We conclude that artesian (above ground) pressure in deep aquifers provides an additional driving mechanism for the delivery of "liquefaction" ejecta to the surface, and contributed to the mess, and repeated mess, of sand, silt and dirty water and the resulting differential ground surface subsidence following shaking. Spatial probability distributions were calculated for observed liquefaction against a range of other shaking and ground strength parameters (Table 1). The relationship between occurrence of liquefaction at the surface and groundwater pressure in the deep aquifers was by far the clearest relationship observed. In detail the spatial probability functions contain a number of features that are a function of our adopted methodology and workflow, so much care is needed in their interpretation. Features of the dataset and methodology will be provided in technical reports and papers elsewhere.

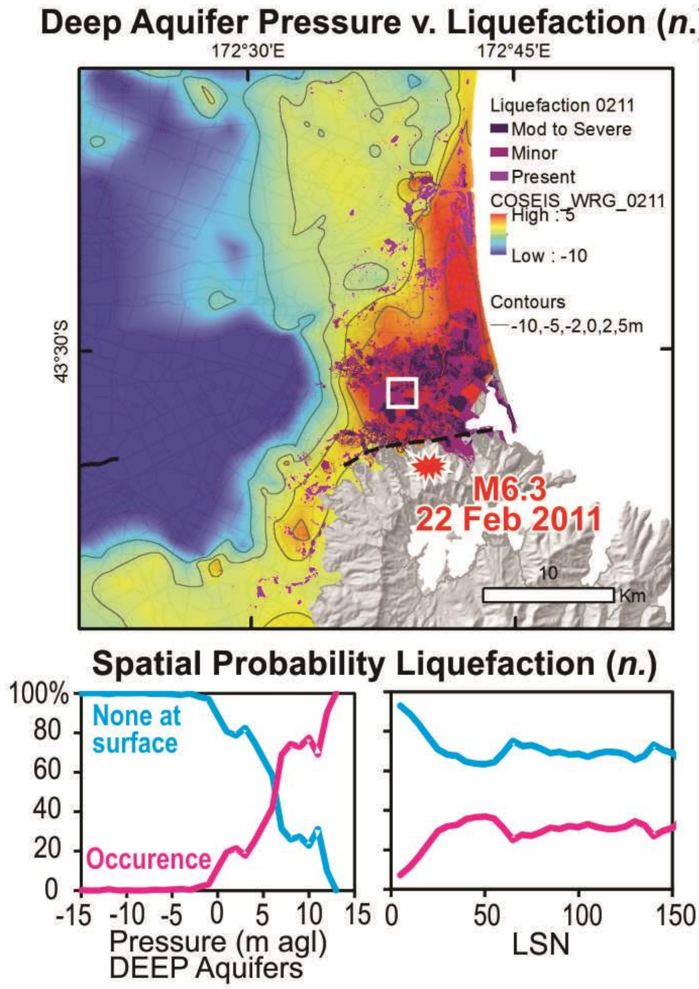

Fig.5 Map showing close relationship of liquefaction (noun), observed at the surface after 22 Feb 2011 Mw6.3 earthquake, with areas where coseismic (dynamic) pressure in deep (>20 m) aquifers was artesian (above ground level 0m above ground level = red). Spatial probability graphs of liquefaction (noun) occurrence at the surface in Christchurch city (pink cf. none observed= blue), comparing deep aquifer pressure against an interpolation of liquefaction severity number (LSN) derived from geotechnical testing that assesses liquefaction (verb). Deep artesian pressure appears to have a strong correlation with liquefaction (noun) indicating it is one of the important factors.

Table 1 List of parameters that were modelled against maps of liquefaction (noun) and liquefaction damage in the Christchurch area following the Mw7.1 Darfield and Mw6.3 Christchurch earthquakes.

Groundwater parameters interpolated from monitoring well data	Static Pressure Deep Aquifers (rel. to ground) Dynamic Pressure Deep Aquifers (coseismic change) Total Pressure Deep Aquifers (rel. to ground) Shallow water table depth ('crust thickness') Confining sediment thickness (isopach) Vertical hydraulic gradient pre-earthquake Vertical hydraulic gradient coseismic
Engineering parameters from CPT data	I_c Soil Behaviour Index q_c cone resistance at 4-5m LPI localised site grid LSN localised site grid LPI Ishikara localised site grid S_{V1D} localised site grid LPI interpolated LSN interpolated CPT Depth of refusal
Shaking parameters interpolated from GeoNet seismometers	PGA horizontal geometric mean PGA vertical PGA Vertical/Horizontal ratio Arias Intensity Total Arias Intensity Vertical Time of shaking >0.5%g Time of shaking >2%g
Other	Elevation rel. to sea level

Objective No. 5
Objective Title: Integration and implementation
Budget: $30k
Objective Achieved? Yes – outcomes 'in progress'

Discussion

We had a specific objective to ensure results were understood by New Zealand geotechnical engineers, hazard assessors and emergency planning groups, and (where applicable) implemented into their process. When this project was initially proposed, we envisaged it might be possible to derive some form of a factor of safety metric that incorporated variations in vertical pressure-gradient (driving force) against aquitard thickness (resistance). In practice, however, we found ejection of material at the surface is most strongly related to absolute groundwater levels, ground shaking in the vertical direction, and only weakly- or un-related to variations in pressure-gradients or aquitard thickness. Incorporating non-hydrostatic pressure gradients in recalculations of CPT-based liquefaction vulnerability parameters (S_{V1D}, LPI, LSN etc) had little effect, and was unable to clearly improve observed versus predicted occurrences across the city. The idea of a factor of safety metric was abandoned while work was focussed on trying to elucidate controlling parameters and mechanisms instead.

Definition of the shallow water table surface and its fluctuation in Christchurch (Objective 1) has been a particularly important, initially unintended, consequence of this project [van Ballegooy et al. 2013, 2014b]. The depth to the water table surface is fundamental when undertaking liquefaction assessments for building foundation design, and surfaces generated are now widely used for liquefaction evaluations to determine appropriate foundation repair and rebuilding approaches. The reports also mapped groundwater fluctuations and highlight the sensitivity of the CPT-based liquefaction vulnerability parameters (S_{V1D}, LPI, LSN etc) to this variability. There is now a realisation that the likelihood of liquefaction is controlled by return periods of BOTH groundwater fluctuations (either seasonal or interannual) AND earthquake shaking, but is currently assessed only on the return period of shaking. A 1 in 500yr shaking event with a median groundwater level may not always be the worst case outcome for liquefaction damage, and there are suburbs in Christchurch with higher groundwater fluctuation where a 1 in 100yr shaking event with a 90th percentile groundwater level (i.e. equivalent to a 1 in 500yr return period liquefaction event) may yield a worse outcome. Engineers are now making more informed models when undertaking their design work as a direct consequence of this project. Quantification of hydrologic responses and aquifer changes as a result of earthquakes has also been considered by regional and district councils elsewhere [e.g. Zemansky et al. 2012].

Dr Sjoerd van Ballegooy has been instrumental in setting up the Canterbury Geotechnical Database [CGD 2015]. He remains a direct advisor to EQC and geotechnical committees, and with Helen Rutter and Simon Cox have been involved in forums and discussion groups centred on Christchurch recovery, and more-recently in the design of an ongoing shallow

groundwater monitoring network (an EQC, CCC, ECan collaboration). The median shallow groundwater reports [van Ballegooy et al. 2013, 2014b] have been delivered via the Canterbury Geotechnical Database (CGD) and continue to provide significant benefits [see Scott et al. in press]. From July 2013-April 2014 (inclusive) there were 4914 views of the median groundwater kmz, peaking at 1047 views during October 2013. Links were also provided via the NZSEE and New Zealand Geotechnical Society "Canterbury Technical Forum" website, which delivers engineering community notices and technical information about the Canterbury Earthquakes and the ongoing recovery process. From March 2013 to April 2014 (inclusive) the median shallow groundwater report summary page was viewed 389 times, and the report pdf downloaded 368 times. GIS data has also been provided direct to users on request, but has not been recorded. These metrics highlight the immediate uptake of the shallow groundwater mapping.

Adoption of the wider results of this study in the long-term (Objectives 3, 4) will depend partly on whether the status quo of liquefaction methodology is seen to be adequate to meet the end-user needs, or whether it can be demonstrated that a change to the current "best practice" is fully warranted. A number of studies have identified disparity between liquefaction (verb) predicted from engineering vulnerability parameters (S_{V1D}, LPI, LSN etc) and observed occurrence of liquefaction and/or resulting damage [Tonkin & Taylor Ltd 2013; van Ballegooy et al. 2014c; Maurer et al. 2014]. There are many potential reasons, such as: local site variability of shaking or geological soil-strength parameters; collection of geotechnical (CPT or SPT) data after earthquakes had already affected soil strength; limited data on coseismic shallow groundwater conditions; calculations that use horizontal accelerations where vertical cause greater fluid pressure increase; and potential contribution from deep potentiometric pressure of aquifers. Transferring the findings will be partly reliant on the existence (in some areas) and quality of groundwater data by regional councils in New Zealand. Understanding places where deep groundwater pressures do NOT present an issue to be concerned about can also be seen as a positive result. While predicting liquefaction is an important component of hazard analysis, it is the severity of liquefaction that is of greater consequence to society and requires a thorough calibration. To that end, this project has deliberately highlighted the difference between liquefaction (verb) and the surface ejection of sand/silt/water material (noun) and the resulting differential ground surface subsidence. A list of published papers, invited talks, conference abstracts and papers, press releases, lectures and other forms of dissemination are provided below.

Outputs & Outcomes

Although the following list is focussed toward this NHRP project, it includes outputs and outcomes that were in part funded by collaborative projects.

Publications

Cox S.C., van Ballegooy S., Rutter H., Wang C-Y, Holden C., Lacrosse V., Manga M. (internal review, June 2015) Liquefaction hazard exacerbated by artesian aquifers. Planning submission to Nature/Nature Geoscience, August 2015.

Gulley, A.K.; Ward, N.F.D.; Cox, S.C.; Kaipio, J.P. 2013. Groundwater responses to the recent Canterbury earthquakes : a comparison. Journal of hydrology, 504: 171-181; doi: 10.1016/j.jhydrol.2013.09.018

O'Brien G.A., Cox S.C., Townend J., Smith E.G.C. (in prep) Systematic earthquake-induced hydrologic changes within the large schist landslides of Cromwell Gorge, New Zealand. About to be submitted to Geofluids.

van Ballegooy, S.; Cox, S.C.; Agnihotri, R.; Reynolds, T.; Thurlow, C.; Rutter, H.K.; Scott, D.M.; Begg, J.G.; McCahon, I. 2013 Median water table elevation in Christchurch and surrounding area after the 4 September 2010 Darfield Earthquake. Lower Hutt: GNS Science. GNS Science report 2013/01. 66 p. + 8 appendices.

van Ballegooy, S.; Cox, S.C.; Thurlow, C.; Rutter, H. K.; Reynolds, T.; Harrington, G.; Fraser, J. Smith, T. 2014. Median water table elevation in Christchurch and surrounding area after the 4 September 2010 Darfield Earthquake: Version 2. GNS Science Report 2014/18, 79 pages + 8 appendices.

Ward, N.F.D (in review 2014/15). On the mechanism of earthquake induced groundwater flow. Submitted to Journal of Hydrology. (Reviews have come back, currently increasing content of article to include analysis of data, and responding to referee issues and recommendations).

Theses and Dissertations

O'Brien G. 2014. Earthquake-induced hydrologic changes in the schist landslides of Cromwell Gorge, Central Otago. Unpublished thesis, Masters in Petroleum Geoscience Victoria University of Wellington.

Gulley A. 2012. Hydrological response to earthquakes. Unpublished BSc(Hons) dissertation, Applied Mathematics, The University of Auckland, 2012.

Conference Presentations

Cox, S.C. 2013. Hydrological effects of Canterbury earthquakes, 2010-2012, New Zealand. Invited presentation H52D_02_AGU2013. AGU Fall meeting, San Francisco, December 2013.

Cox, S.C.; Rutter H. 2013 Natural and earthquake-related water table fluctuations beneath Christchurch city. Abstract. New Zealand Hydrological Society Conference, Palmerston North, November 2013. 2 pages.

Cox, S.C.; van Ballegooy, S.; Begg, J.G.; Rutter, H.J. 2013 Inter-annual, seasonal and earthquake-induced fluctuations in water table elevation, with implications for studies of liquefaction in Christchurch. p. 21-22 IN: Reid, C.M. (conference convener)

Geosciences 2013 : Annual Conference of the Geoscience Society of New Zealand : abstracts. : Geoscience Society of New Zealand. Geoscience Society of New Zealand miscellaneous publication 136A.

Dudley Ward, N. 2014. About the Christchurch Earthquakes of 2010-2011 – Earthquakes, groundwater, (and the Tsunami that never was). 1st ASCETE Sudelfeld Summit. Workshop on advanced numerical methods for earthquake and tsunami simulation on modern HPC systems.

Gulley, A.K.; Dudley Ward, N.F.; Cox, S.C.; Kaipio, J.P. 2013 Analysis and modelling of borehole piezometric responses due to Canterbury earthquakes. p. 38 IN: Reid, C.M. (conference convener) Geosciences 2013 : Annual Conference of the Geoscience Society of New Zealand : abstracts. Geoscience Society of New Zealand. Geoscience Society of New Zealand miscellaneous publication 136A.

O'Brien, G.; Townend, J.; Cox, S.C.; Smith, E.G.C. 2013 The hydraulic response of schist landslides to regional earthquakes in Central Otago. p. 71 IN: Reid, C.M. (conference convener) Geosciences 2013 : Annual Conference of the Geoscience Society of New Zealand : abstracts. [Christchurch]: Geoscience Society of New Zealand. Geoscience Society of New Zealand miscellaneous publication 136A.

Scott, J.W.; van Ballegooy, S.; Stannard M., Lacrosse, V., Russell J. 2015 (in press). The benefits and opportunities of a shared geotechnical database. Paper for the 6th International Conference on Earthquake Geotechnical Engineering, 1-4 Nov 2015, Christchurch, New Zealand. 12 pages.

Steinhage, F.; Rutter, H.K.; Cox, S.C. 2014 Surface water - groundwater interaction, lower Avon/Otakaro River, Christchurch. New Zealand. p. 234 In: 2014 Water Symposium: integration, the final frontier. New Zealand Hydrological Society Conference 24-28 Nov 2014, Blenheim.

van Ballegooy, S.; Thurlow, C.; Reynolds, T.; Cox, S.C. 2013 Development of a median groundwater table surface for Christchurch. p. 322-329 IN: Chin, C.Y. (ed) 19th New Zealand Geotechnical Society 2013 Symposium : Hanging by a thread? : lifelines, infrastructure and natural disasters, Queenstown, November 2013 : [proceedings]. Wellington, NZ: Institute of Professional Engineers New Zealand. Proceedings of technical groups (Institution of Professional Engineers New Zealand) 38(1)GM.

Other Communications and Outreach

Technical presentations, lectures and seminars:
van Ballegooy and Cox gave presentations on 6 March 2013 “Shallow groundwater levels in greater Christchurch” to a meeting geotechnical engineers working for the private insurers, then subsequently to the Canterbury Technical Forum on 6 March 2013. Forum meetings are collaboration between the NZSEE, the NZ Geotechnical Society (NZGS), the Structural Engineering Society NZ (SESOC) and the Canterbury Structural Group (CSG). Approximately 200 members were present.

Cox gave seminars “Evidence that artesian groundwater DID contribute to Christchurch liquefaction and lateral spreading damage“ at GNS Science on 23 Feb 2015 (Audience ~50), and Tonkin & Taylor Ltd on 25 Feb 2015 (Audience ~25).

Cox gave lectures on ‘The Canterbury Earthquake sequence and liquefaction hazard’ during a sabbatical in Europe. (CNRS Institut de Physique du Globe de Paris – June 2013; University of

Lausanne – July 2013; University of Southampton (Ocean and Earth Sciences) – July 2013; University of California Berkeley – Aug 2013).

Media releases:
13 April 2012: http://www.sciencemediacentre.co.nz/2012/04/13/government-injects-7m-into-hazards-research/
24 May 2012: http://www.odt.co.nz/news/dunedin/210419/project-may-elucidate-liquefaction
30 May 2012: http://www.stuff.co.nz/the-press/news/7011702/Aquifer-role-in-liquefaction-studied

Databases

GNS Science reports SR 2014/18 and 2013/01 and appendix datasets relating to the modelled water table depth and the effects of the earthquakes, are delivered via the Canterbury Geotechnical Database (CGD). Science reports are also available from the GNS website.
https://canterburygeotechnicaldatabase.projectorbit.com/Registration/Login.aspx?ReturnUrl=%2fSitePages%2fHome.aspx

Relevant raw data on groundwater and earthquakes is held by ECAN and GeoNet. GNS Science holds an extensive and large ArcGIS dataset of classified boreholes, groundwater conditions and changes during the earthquakes that is presently being documented with metadata. We are searching for an appropriate location to serve all these data.

Capability Development

Grant O'Brien employed as a VUW summer research assistant (Dec 2012-Feb 2013), helped to work on water table changes. Grant gained an OMV scholarship and went on to enrol in MSc at Victoria studying hydrological effects of earthquakes on landslides in the Cromwell Gorge, which he submitted in April 2014. Thesis was co-supervised by Simon Cox.

Anton Gully was employed by OCMO as a summer research student and his work formed the foundation of the Gulley et al. 2013 paper, and some of the work in his 4th year dissertation that was co-supervised by Nick Dudley Ward. Anton has since enrolled in for a PhD in seismology at Auckland University.

Annabeth Cohen has been employed as a part-time research assistant (March 2014-Dec 2014). She also developed knowledge about the hydrological effects of earthquakes. Franziska Steinhage, an 'Environmental Science' student from the Eberhard Karls University Tübingen in Germany undertook an internship at GNS Science/Aqualinc during 2014. She monitored tidal fluctuations in the Avon River and nearby groundwater, that will provide baseline data for future modelling of shallow groundwater surfaces.

List of Key End-users

- **Earthquake Commission (EQC)**
- **Canterbury Earthquake Recovery Authority (CERA)**
- **Environment Canterbury Regional Council (ECan)**
- **Christchurch City Council (CCC)**
- **Other scientists/science**
- **Canterbury engineers and geotechnical engineers (NZSEE & NZGS)**
- **New Zealand insurance and re-insurance industry**

Conclusions and Recommendations

'Liquefaction' is commonly used as a verb describing the process when an earthquake causes poorly consolidated, groundwater-saturated, geological materials to temporarily lose strength and stiffness, due to increased pore pressure in the material and permanently volumetrically consolidate. By way of contrast, the term 'liquefaction' became a New Zealand household noun describing the vast quantities of soul-destroying sand, silt and smelly water that repeatedly inundated properties during the 2010-2011 Canterbury earthquake sequence resulting in differential ground surface subsidence. Liquefaction verb and noun were extreme in their combined devastation of Christchurch city and provide a world-class example of this natural hazard.

This Natural Hazards Research Platform project 2012-GNS-05 addressed a hypothesis "Did artesian groundwater contribute to Christchurch liquefaction and lateral spreading damage?". The results are conclusive. We demonstrate strong spatial correlations between the occurrence (and severity) of ejected material and liquefaction-related ground damage with deep groundwater pressure in aquifers beneath the city.

Present geotechnical best-practice assessment of liquefaction hazard typically only considers the shallow water table position and assumes a hydrostatic pressure profile below the shallow groundwater surface. Our results suggest where groundwater pressure is artesian (above ground) there is an additional driving mechanism for the surface ejection of liquefied material, and that liquefaction triggering may also be exacerbated by the transfer of groundwater from deep to shallow aquifers. Artesian aquifer systems and high groundwater pressure, whilst providing benefits in terms of quality water supplies, appear to be a significant and as yet little recognised, geological hazard.

While liquefied ground presents an engineering challenge, the repeated invasion of properties by ejecta and the resulting differential ground surface subsidence also adds a heavy societal cost to this hazard. Confined artesian groundwater presents a unique hazard where sand, silt and dirty water can be repeatedly transported to the surface following shaking, but not all confined systems will have the same sensitivity given similar levels of ground shaking. Sustainable development on liquefaction susceptible soil deposits overlying artesian aquifers is dependent on the thickness of the non-liquefying surface layers (often influenced by the depth to the shallow groundwater surface), the soil characteristics of the underlying liquefying soil layers and as this study has found may also be dependent on the thickness, strength and integrity of the confining layers between the liquefying soil deposits and the underlying artesian aquifer and the amount of pressure in the underlying aquifer. Aquitards enable land to remain above static water levels, in the absence of which, land would become flooded.

The contribution of artesian groundwater pressure to liquefaction had been postulated previously on the basis of distal liquefaction occurring far from earthquake epicentres and local observations [Wang 2007; Cox et al. 2012], but the process has never been conclusively demonstrated. Unprecedented groundwater monitoring and geotechnical datasets in Canterbury enabled this study to test the hypothesis and demonstrate that artesian groundwater pressure was one of the contributors to the extent and severity of the Christchurch liquefaction ejected to the surface. A corollary is that during the evaluation of liquefaction potential of a site, it is important to consider the hydrogeologic environment of

the site, in addition to evaluating the liquefaction triggering resistance of the soils in isolation. Highlighted by recent events in Christchurch, this is an internationally significant, yet surprisingly overlooked issue that has far-reaching implications for hazard assessment [Wang 2007]. Most importantly, we need to be wary that if Christchurch were to be adopted as a national or world-wide example of the hazard and its consequence, there is very real chance legislation and insurance could mitigate perceived rather than actual hazards elsewhere. Liquefaction hazard and risk assessments need to consider deep potentiometric pressure, natural fluctuations, and the potential for earthquake-induced pressure change, in addition to the shallow ground water surface.

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